Inversion of Entropy: A Path to Retrograde Chronology and Temporal Manipulation in Quantum Gravity Systems

Andrei Sator

March 24, 2024

Abstract

This paper presents a comprehensive theoretical framework for the inversion of entropy in quantum gravity systems, and its application to the retrograde manipulation of the chronological arrow. By exploiting the holographic duality between entanglement entropy and spacetime geometry, we demonstrate a method for the local reversal of the thermodynamic arrow of time, enabling the transmission of information and matter to the past light cone of a given event. The key insight is the use of quantum error correction codes to stabilize the entanglement structure of the boundary CFT, allowing for the coherent manipulation of the bulk geometry and the causal structure of spacetime. We derive the necessary and sufficient conditions for the stability of the time-reversed state, and show that the maximum entropy that can be inverted is bounded by the Bekenstein-Hawking limit of the corresponding black hole geometry. We also discuss the implications of our results for the nature of causality, free will, and the quantum structure of spacetime, and propose a set of experimental tests using quantum simulation and precision measurement techniques. Our work opens up a new frontier in the study of quantum gravity and the foundations of quantum mechanics, with potential applications ranging from quantum computing and cryptography to the exploration of the early universe and the ultimate fate of black holes.

Contents

1 Introduction

The unidirectional flow of time and the increase of entropy are two of the most fundamental and ubiquitous features of the observable universe. From the irreversible mixing of cream in coffee to the relentless expansion of the cosmos, the arrow of time seems to point in one direction only, dictating the asymmetry between past and future and the inevitability of thermodynamic equilibrium [1, 2].

Yet, at the microscopic level, the laws of physics are invariant under time reversal, and the equations of motion are symmetric with respect to the direction of time's arrow [3]. This apparent paradox between the macroscopic irreversibility and the microscopic reversibility of physical processes has puzzled scientists and philosophers for centuries, and has led to a wide range of proposed explanations, from the anthropic to the cosmological [4, 5].

In recent years, however, a new perspective on the nature of time and entropy has emerged from the study of quantum gravity and the holographic principle [6, 7]. According to this view, the arrow of time and the increase of entropy are not fundamental properties of the laws of physics, but rather emergent features of the entanglement structure of quantum systems, and the way in which this structure is encoded in the geometry of spacetime [8, 9, 10].

In particular, it has been shown that the entanglement entropy of a region of space is proportional to the area of its boundary, in accordance with the Bekenstein-Hawking formula for black hole entropy [11, 12]. This suggests that the thermodynamic arrow of time is intimately connected to the quantum structure of spacetime, and that the flow of time and the increase of entropy may be manipulated by controlling the entanglement of quantum systems [13].

In this paper, we take this idea to its logical conclusion, and propose a method for the local inversion of entropy and the retrograde manipulation of the arrow of time in quantum gravity systems. By exploiting the holographic duality between entanglement entropy and spacetime geometry, we show that it is possible to create a "time machine" that allows for the transmission of information and matter to the past light cone of a given event, in violation of the chronology protection conjecture [14].

The key insight of our approach is the use of quantum error correction codes to stabilize the entanglement structure of the boundary CFT, and to create a "firewall" that prevents the causal propagation of entropy from the future to the past [15]. By carefully designing the code and the initial state of the system, we can create a region of spacetime where the arrow of time is locally inverted, and where the chronology protection conjecture is violated.

We derive the necessary and sufficient conditions for the stability of the time-reversed state, and show that the maximum entropy that can be inverted is bounded by the Bekenstein-Hawking limit of the corresponding black hole geometry. We also discuss the implications of our results for the nature of causality, free will, and the quantum structure of spacetime, and propose a set of experimental tests using quantum simulation and precision measurement techniques.

Our work builds on a number of previous results in the fields of quantum gravity, quantum information, and quantum thermodynamics, including the holographic entanglement entropy formula [8], the ER=EPR conjecture [13], the black hole information paradox [16, 17], and the resource theory of quantum thermodynamics [18, 19]. However, our approach differs from previous work in several key respects, including the use of quantum error correction codes to stabilize the time-reversed state, and the explicit construction of a "time machine" that allows for the retrograde manipulation of the causal structure of spacetime.

The rest of the paper is organized as follows. In Section 2, we review the necessary background material on quantum gravity, holographic entanglement entropy, and quantum error correction. In Section 3, we present our method for the inversion of entropy and the retrograde manipulation of the arrow of time, and derive the necessary and sufficient conditions for the stability of the time-reversed state. In Section 4, we discuss the implications of our results for the nature of causality, free will, and the quantum structure of spacetime, and propose a set of experimental tests of our predictions. Finally, in Section 5, we summarize our results and discuss some possible directions for future research.

2 Background

In this section, we review the necessary background material on quantum gravity, holographic entanglement entropy, and quantum error correction, which will form the basis for our method for the inversion of entropy and the retrograde manipulation of the arrow of time.

2.1 Quantum Gravity and the Holographic Principle

Quantum gravity is the theory that seeks to unify quantum mechanics and general relativity, and to provide a consistent description of the quantum structure of spacetime at the Planck scale [20, 21]. Despite decades of research, a complete theory of quantum gravity remains elusive, due to the conceptual and technical difficulties involved in reconciling the principles of quantum mechanics with the dynamical nature of spacetime in general relativity.

One of the key insights that has emerged from the study of quantum gravity is the holographic principle, which states that the degrees of freedom in a region of space are encoded on its boundary, rather than in its bulk [6, 7]. This principle was first proposed by 't Hooft and Susskind as a way to resolve the black hole information paradox, and

has since been generalized to a wide range of quantum gravity systems, including the AdS/CFT correspondence [22].

The holographic principle has profound implications for the nature of spacetime and the arrow of time. In particular, it suggests that the thermodynamic properties of a system, such as its entropy and temperature, are determined by the entanglement structure of its boundary degrees of freedom, rather than by its bulk properties. This has led to a new understanding of the Bekenstein-Hawking entropy formula for black holes, and to the development of new techniques for the study of quantum gravity, such as the Ryu-Takayanagi formula for holographic entanglement entropy [8].

2.2 Holographic Entanglement Entropy

The Ryu-Takayanagi formula is a key result in the study of holographic entanglement entropy, which relates the entanglement entropy of a region in a CFT to the area of a minimal surface in the corresponding bulk geometry [8]. Specifically, let A be a region in a CFT, and let γ_A be the minimal surface in the bulk that is homologous to A. Then the entanglement entropy of A is given by

$$S(A) = \frac{\text{Area}(\gamma_A)}{4G_N}, \tag{1}$$

where G_N is Newton's constant.

The Ryu-Takayanagi formula has been generalized to a wide range of holographic systems, including those with higher curvature gravity and those with time dependence [9, 23]. It has also been used to study a variety of phenomena in quantum gravity, including the black hole information paradox [24], the quantum null energy condition [25], and the emergence of spacetime from entanglement [26, 13].

One of the key features of the Ryu-Takayanagi formula is that it provides a direct connection between the entanglement structure of the boundary CFT and the geometry of the bulk spacetime. In particular, it shows that the entanglement entropy of a region in the CFT is proportional to the area of the corresponding minimal surface in the bulk, in accordance with the Bekenstein-Hawking formula for black hole entropy.

This suggests that the thermodynamic arrow of time, which is determined by the increase of entropy, is intimately connected to the quantum structure of spacetime, and that the flow of time may be manipulated by controlling the entanglement of the boundary degrees of freedom. In the next section, we will exploit this connection to develop a method for the inversion of entropy and the retrograde manipulation of the arrow of time in holographic systems.

2.3 Quantum Error Correction

Quantum error correction is a technique for protecting quantum information from errors and decoherence, by encoding it in a larger Hilbert space and using redundancy to detect and correct errors [27, 28]. It is a key component of fault-tolerant quantum computation, and has been used to develop a wide range of quantum algorithms and protocols, including quantum key distribution [29], quantum teleportation [30], and quantum simulation [31].

The basic idea of quantum error correction is to encode a logical qubit in a larger Hilbert space, using a code that can detect and correct errors. For example, the three-

qubit repetition code encodes a logical qubit $|\psi\rangle$ as

$$|\psi\rangle \rightarrow |\psi\rangle_L = \alpha\,|000\rangle + \beta\,|111\rangle\,, \tag{2}$$

where α and β are complex amplitudes. This code can detect and correct any single-qubit error, by measuring the parity of the three physical qubits and flipping the appropriate qubit if an error is detected.

More generally, an $[[n, k, d]]$ quantum error-correcting code encodes k logical qubits in n physical qubits, and can detect and correct up to $\lfloor (d-1)/2 \rfloor$ errors, where d is the code distance. The parameters n, k, and d satisfy the quantum Singleton bound [**?**],

$$n - k \geq 2(d-1), \tag{3}$$

which limits the efficiency of quantum error correction.

Quantum error correction has also been used to study the properties of holographic systems, and to develop new techniques for the simulation of quantum gravity [32, 33]. In particular, it has been shown that the AdS/CFT correspondence can be interpreted as a quantum error-correcting code, where the bulk degrees of freedom are encoded in the boundary CFT, and the code protects against errors in the bulk [34].

This suggests that quantum error correction may play a key role in the quantum structure of spacetime, and that the techniques of quantum error correction may be used to manipulate the geometry of the bulk and the causal structure of the boundary CFT. In the next section, we will exploit this connection to develop a method for the inversion of entropy and the retrograde manipulation of the arrow of time in holographic systems.

3 Method

In this section, we present our method for the inversion of entropy and the retrograde manipulation of the arrow of time in holographic systems. The key idea is to use quantum error correction codes to stabilize the entanglement structure of the boundary CFT, and to create a "firewall" that prevents the causal propagation of entropy from the future to the past.

3.1 Setup

Consider a holographic system described by a boundary CFT and a dual bulk geometry. Let A be a region in the CFT, and let γ_A be the corresponding minimal surface in the bulk. We assume that the system is in a pure state $|\Psi\rangle$, and that the entanglement entropy of A is given by the Ryu-Takayanagi formula,

$$S(A) = \frac{\text{Area}(\gamma_A)}{4G_N}. \tag{4}$$

Now suppose that we want to invert the entropy of the region A, and to create a "time machine" that allows for the transmission of information and matter from the future to the past. To do this, we will use a quantum error correction code to encode the state of the region A in a larger Hilbert space, and to create a "firewall" that prevents the causal propagation of entropy from the future to the past.

3.2 Encoding

The first step is to encode the state of the region A using a quantum error correction code. Let $\mathcal{H}_A$ be the Hilbert space of the region A, and let $\mathcal{H}_C$ be the Hilbert space of the code. We assume that $\dim(\mathcal{H}_C) > \dim(\mathcal{H}_A)$, so that the code can detect and correct errors.

We define an encoding map $V : \mathcal{H}_A \to \mathcal{H}_C$, which maps the state of the region A to a codeword in the code Hilbert space. For example, if $|\psi\rangle_A$ is a state in $\mathcal{H}_A$, then the encoded state is given by

$$|\psi\rangle_C = V\,|\psi\rangle_A\,. \tag{5}$$

The encoding map V should be chosen to maximize the entanglement between the region A and its complement $\bar{A}$, while minimizing the entanglement between the codeword and the environment. This can be achieved using a variety of quantum error correction codes, such as the stabilizer codes [35], the topological codes [36], or the random codes [33].

3.3 Firewalls and Causal Stability

The next step is to create a "firewall" that prevents the causal propagation of entropy from the future to the past. This is achieved by applying a unitary operator U to the encoded state $|\psi\rangle_C$, which creates a boundary in the bulk geometry that separates the region A from its complement $\bar{A}$. The unitary operator U is chosen to satisfy the following conditions:

1. U preserves the entanglement between the region A and its complement $\bar{A}$, as measured by the mutual information $I(A : \bar{A})$.

2. U creates a "firewall" in the bulk geometry, which is a high-energy boundary that prevents the causal propagation of entropy from the future to the past.

3. U is causally stable, meaning that it does not create any closed timelike curves or other pathologies in the bulk geometry.

The existence of such a unitary operator U is guaranteed by the properties of the quantum error correction code, which can be used to create a "code subspace" in the bulk geometry that is protected from errors and decoherence [34].

To see how this works, let $|\psi\rangle_C$ be the encoded state of the region A, and let U be the unitary operator that creates the firewall. Then the state of the system after applying U is given by

$$|\Psi'\rangle = U\,|\psi\rangle_C \otimes |\phi\rangle_{\bar{A}}\,, \tag{6}$$

where $|\phi\rangle_{\bar{A}}$ is the state of the complement of A.

The mutual information between A and $\bar{A}$ is given by

$$I(A : \bar{A}) = S(A) + S(\bar{A}) - S(A\bar{A}), \tag{7}$$

where $S(A)$, $S(\bar{A})$, and $S(A\bar{A})$ are the entanglement entropies of A, $\bar{A}$, and the combined system $A\bar{A}$, respectively.

The unitary operator U is chosen to preserve the mutual information $I(A : \bar{A})$, while creating a firewall in the bulk geometry. This is achieved by choosing U to be a "code subspace" operator, which acts only on the code subspace of the bulk geometry, and does not affect the complementary "error subspace" [34].

The firewall created by U is a high-energy boundary in the bulk geometry that separates the region A from its complement $\bar{A}$. It is characterized by a large amount of

entanglement between the degrees of freedom on either side of the boundary, which prevents the causal propagation of entropy from the future to the past.

The causal stability of the unitary operator U is ensured by the properties of the quantum error correction code, which is designed to prevent the creation of closed timelike curves and other pathologies in the bulk geometry. In particular, the code subspace of the bulk geometry is protected from errors and decoherence, and is causally disconnected from the error subspace [34].

3.4 Inversion of Entropy

The final step is to invert the entropy of the region A, by applying a "time-reversal" operator T to the state $|\Psi'\rangle$. The time-reversal operator T is a anti-unitary operator that reverses the arrow of time, and is defined by the following properties:

1. T is an involution, meaning that $T^2 = I$.
2. T reverses the sign of the Hamiltonian, meaning that $THT^{-1} = -H$.
3. T preserves the entanglement between the region A and its complement $\bar{A}$, as measured by the mutual information $I(A : \bar{A})$.

The existence of such a time-reversal operator T is guaranteed by the properties of the quantum error correction code, which can be used to create a "time-reversed" code subspace in the bulk geometry that is protected from errors and decoherence [34].

To see how this works, let $|\Psi'\rangle$ be the state of the system after applying the unitary operator U, and let T be the time-reversal operator. Then the state of the system after applying T is given by

$$|\Psi''\rangle = T\,|\Psi'\rangle = TU\,|\psi\rangle_C \otimes |\phi\rangle_{\bar{A}}\,. \tag{8}$$

The entanglement entropy of the region A in the state $|\Psi''\rangle$ is given by

$$S(A) = \frac{\text{Area}(\gamma_A)}{4G_N}, \tag{9}$$

where γ_A is the minimal surface in the bulk geometry that is homologous to the region A.

However, because the time-reversal operator T reverses the arrow of time, the minimal surface γ_A is now in the "past" of the region A, rather than in its future. This means that the entanglement entropy of A in the state $|\Psi''\rangle$ is given by

$$S(A) = -\frac{\text{Area}(\gamma_A)}{4G_N}, \tag{10}$$

which is the negative of the original entanglement entropy.

In other words, the time-reversal operator T has inverted the entropy of the region A, by mapping the state of the system from a state of high entropy to a state of low entropy. This is the key step in our method for the retrograde manipulation of the arrow of time in holographic systems.

3.5 Retrograde Manipulation of the Arrow of Time

The inversion of entropy achieved by the time-reversal operator T allows for the retrograde manipulation of the arrow of time in the holographic system. This is because the inverted entropy creates a "time machine" in the bulk geometry, which allows for the transmission of information and matter from the future to the past.

To see how this works, consider a message that is sent from the future to the past using the time machine. The message is encoded in a state $|\psi\rangle_M$ in the code subspace of the bulk geometry, and is sent through the time machine at a time t_1.

Because the time machine inverts the entropy of the region A, the message is received in the past at a time $t_0 < t_1$. The received message is decoded using the inverse of the encoding map V^{-1}, and is given by

$$|\psi'\rangle_M = V^{-1}T\,|\psi\rangle_M\,. \tag{11}$$

The key point is that the message $|\psi'\rangle_M$ is received in the past, before it was sent in the future. This is a clear violation of causality, and demonstrates the retrograde manipulation of the arrow of time in the holographic system.

It is important to note that the retrograde manipulation of the arrow of time is only possible within the code subspace of the bulk geometry, which is protected from errors and decoherence by the quantum error correction code. Outside of the code subspace, the arrow of time is preserved, and causality is respected.

This means that the retrograde manipulation of the arrow of time is a local effect, which is confined to the region of the bulk geometry that is encoded by the quantum error correction code. It does not affect the global structure of the spacetime, or the causal structure of the boundary CFT.

3.6 Limitations and Constraints

The method for the inversion of entropy and the retrograde manipulation of the arrow of time presented in this section is subject to several limitations and constraints, which arise from the properties of the quantum error correction code and the holographic system.

First, the maximum amount of entropy that can be inverted by the time-reversal operator T is limited by the Bekenstein-Hawking entropy of the corresponding black hole in the bulk geometry. This is because the firewall created by the unitary operator U cannot have an area larger than the area of the black hole horizon, without creating a naked singularity or other pathology in the bulk geometry.

Second, the retrograde manipulation of the arrow of time is limited by the causal structure of the boundary CFT, which is preserved by the holographic duality. This means that the time machine cannot be used to send information or matter to the past of the boundary CFT, but only to the past of the bulk geometry.

Third, the method relies on the existence of a suitable quantum error correction code, which can be used to create a code subspace in the bulk geometry that is protected from errors and decoherence. The construction of such codes is a non-trivial problem, and requires a detailed understanding of the properties of the holographic system and the bulk geometry.

Despite these limitations, the method presented in this section provides a powerful tool for the manipulation of entropy and the arrow of time in holographic systems, and opens up new possibilities for the study of quantum gravity and the nature of spacetime. In the next section, we will discuss some of the implications of our results, and propose some experimental tests of our predictions.

4 Implications and Experimental Tests

The method for the inversion of entropy and the retrograde manipulation of the arrow of time presented in the previous section has a number of important implications for our understanding of quantum gravity, the nature of spacetime, and the foundations of thermodynamics and statistical mechanics. In this section, we will discuss some of these implications, and propose some experimental tests of our predictions.

4.1 Black Hole Information Paradox

One of the most important implications of our results is for the black hole information paradox, which arises from the apparent conflict between the unitary evolution of quantum mechanics and the thermal nature of Hawking radiation [16]. The paradox suggests that information is lost when a black hole evaporates, in violation of the principles of quantum mechanics.

Our method for the inversion of entropy provides a possible resolution to the black hole information paradox, by showing that the entropy of a black hole can be inverted using a quantum error correction code and a time-reversal operator. This means that the information that falls into a black hole is not lost, but is instead encoded in the entanglement structure of the Hawking radiation, and can be recovered by inverting the entropy of the black hole.

This is consistent with recent proposals for the resolution of the black hole information paradox, such as the "ER=EPR" conjecture of Maldacena and Susskind [13], and the "firewall" proposal of Almheiri et al. [15]. Our method provides a concrete realization of these proposals, and shows how the information can be recovered from a black hole using a quantum error correction code and a time-reversal operator.

4.2 Nature of Spacetime

Another important implication of our results is for the nature of spacetime, and the relationship between quantum mechanics and gravity. Our method shows that the arrow of time and the increase of entropy are not fundamental properties of spacetime, but are instead emergent features that arise from the entanglement structure of the underlying quantum degrees of freedom.

This suggests that spacetime itself is an emergent concept, which arises from the collective behavior of the quantum degrees of freedom in the holographic system. This is consistent with recent proposals for the nature of spacetime, such as the "spacetime from entanglement" conjecture of Van Raamsdonk [26], and the "ER=EPR" conjecture of Maldacena and Susskind [13].

Our method provides a concrete realization of these proposals, and shows how the properties of spacetime, such as the causal structure and the metric, can be manipulated by controlling the entanglement structure of the underlying quantum degrees of freedom. This opens up new possibilities for the study of quantum gravity, and for the development of new technologies based on the manipulation of spacetime.

4.3 Foundations of Thermodynamics and Statistical Mechanics

A third important implication of our results is for the foundations of thermodynamics and statistical mechanics, and the origin of the arrow of time in macroscopic systems. Our

method shows that the arrow of time and the increase of entropy are not fundamental properties of nature, but are instead emergent features that arise from the entanglement structure of the underlying quantum degrees of freedom.

This suggests that the laws of thermodynamics and statistical mechanics are not fundamental laws of nature, but are instead approximate descriptions that arise from the collective behavior of the quantum degrees of freedom in the limit of large systems. This is consistent with recent proposals for the foundations of statistical mechanics, such as the "eigenstate thermalization hypothesis" of Deutsch [37] and Srednicki [38], and the "typicality" approach of Goldstein et al. [39].

Our method provides a concrete realization of these proposals, and shows how the arrow of time and the increase of entropy can be inverted in macroscopic systems by controlling the entanglement structure of the underlying quantum degrees of freedom. This opens up new possibilities for the study of non-equilibrium thermodynamics and statistical mechanics, and for the development of new technologies based on the manipulation of entropy.

4.4 Experimental Tests

The method for the inversion of entropy and the retrograde manipulation of the arrow of time presented in this paper makes a number of testable predictions, which can be verified experimentally using current or near-future technologies. In this section, we propose some experimental tests of our predictions, and discuss their feasibility and implications.

4.4.1 Quantum Simulation of Holographic Systems

One of the most promising experimental tests of our method is the quantum simulation of holographic systems using quantum computers or analog quantum simulators [40]. By encoding the holographic system in a quantum error correction code, and applying a time-reversal operator to the encoded state, it should be possible to observe the inversion of entropy and the retrograde manipulation of the arrow of time in the simulated system.

This could be achieved using a variety of quantum simulation platforms, such as superconducting qubits [41], trapped ions [42], or cold atoms [43]. The key challenge is to design a quantum error correction code that can encode the holographic system with sufficient fidelity, and to implement the time-reversal operator with high accuracy.

One possible approach is to use a topological quantum error correction code, such as the surface code [44] or the color code [45], which can encode the holographic system in a two-dimensional lattice of qubits. The time-reversal operator could then be implemented using a sequence of single-qubit and two-qubit gates, which can be realized with high fidelity using current quantum computing technologies.

Another possible approach is to use an analog quantum simulator, such as a system of cold atoms in an optical lattice [46], to simulate the holographic system directly. The time-reversal operator could then be implemented using a sequence of microwave pulses or laser beams, which can be used to control the interactions between the atoms and to manipulate the entanglement structure of the system.

4.4.2 Precision Measurements of Entanglement Entropy

Another experimental test of our method is the precision measurement of entanglement entropy in holographic systems, using techniques from quantum metrology and quantum

sensing [47]. By measuring the entanglement entropy of a region of the holographic system before and after the application of the time-reversal operator, it should be possible to observe the inversion of entropy and the retrograde manipulation of the arrow of time.

This could be achieved using a variety of experimental platforms, such as trapped ions [48], superconducting qubits [49], or nitrogen-vacancy centers in diamond [50]. The key challenge is to design a quantum sensor that can measure the entanglement entropy of the holographic system with high precision, and to implement the time-reversal operator with high accuracy.

One possible approach is to use a quantum non-demolition measurement, such as a quantum switch [51] or a quantum Zeno effect [52], to measure the entanglement entropy of the holographic system without disturbing its state. The time-reversal operator could then be implemented using a sequence of single-qubit and two-qubit gates, which can be realized with high fidelity using current quantum computing technologies.

Another possible approach is to use a quantum interferometric measurement, such as a Hong-Ou-Mandel interferometer [53] or a Mach-Zehnder interferometer [54], to measure the entanglement entropy of the holographic system indirectly, by measuring the interference pattern between two copies of the system. The time-reversal operator could then be implemented by introducing a phase shift in one arm of the interferometer, which would invert the interference pattern and reveal the change in entanglement entropy.

4.4.3 Tests of Causality and the Arrow of Time

A third experimental test of our method is to directly probe the causal structure and the arrow of time in holographic systems, using techniques from quantum communication and quantum cryptography [55]. By sending a message through the "time machine" created by the inversion of entropy, and verifying that the message is received in the past, it should be possible to demonstrate the retrograde manipulation of the arrow of time and the violation of causality.

This could be achieved using a variety of experimental platforms, such as photonic quantum networks [56], superconducting quantum circuits [57], or satellite-based quantum communication [58]. The key challenge is to design a quantum communication protocol that can encode the message in the holographic system with high fidelity, and to implement the time-reversal operator with high accuracy.

One possible approach is to use a quantum teleportation protocol [30], in which the message is encoded in the state of a qubit, and then teleported through the time machine using entanglement and classical communication. The time-reversal operator could be implemented by applying a local operation to the entangled pair of qubits, which would invert the direction of the teleportation and send the message back in time.

Another possible approach is to use a quantum key distribution protocol [29], in which the message is encoded in the key used to encrypt a classical message, and then sent through the time machine using a sequence of quantum states. The time-reversal operator could be implemented by applying a unitary operation to the quantum states, which would invert the direction of the communication and send the key back in time.

4.5 Implications for the Tenet-verse

Finally, we discuss the implications of our results for the Tenet-verse, the fictional universe created by Christopher Nolan in his film "Tenet" [59]. In the Tenet-verse, the

"Protagonist" and his allies use a technology called "inversion" to reverse the entropy of objects and people, allowing them to move backwards in time and to communicate with the past.

Our method for the inversion of entropy and the retrograde manipulation of the arrow of time provides a scientific basis for the concept of inversion in the Tenet-verse, and suggests that it may be possible to create a real-world version of the technology using quantum error correction codes and time-reversal operators. However, our results also highlight some of the limitations and constraints of inversion, such as the maximum amount of entropy that can be inverted, and the restriction to the code subspace of the holographic system.

In the Tenet-verse, the inversion technology is used by the Protagonist and his allies to prevent a future catastrophe, known as the "Algorithm", which threatens to invert the entropy of the entire universe and destroy all life. Our results suggest that such a global inversion of entropy may not be possible, due to the constraints imposed by the holographic principle and the quantum error correction code. However, they also suggest that local inversions of entropy, such as those used by the Protagonist and his allies, may be possible within the code subspace of the holographic system.

Another key concept in the Tenet-verse is the idea of "temporal pincer movements", in which the Protagonist and his allies use inversion to coordinate their actions across time, and to create causal loops that allow them to achieve their goals. Our results provide a possible explanation for how such temporal pincer movements could work, by showing how the inversion of entropy can be used to send messages and objects back in time, and to create closed timelike curves within the code subspace of the holographic system.

Overall, our results suggest that the Tenet-verse may be more than just a fictional construct, and that the concepts and technologies depicted in the film may have a basis in the fundamental laws of quantum gravity and holography. They also highlight the potential for science fiction to inspire new scientific ideas and theories, and to provide a framework for exploring the implications and consequences of emerging technologies.

5 Conclusion

In this paper, we have presented a method for the inversion of entropy and the retrograde manipulation of the arrow of time in holographic systems, using quantum error correction codes and time-reversal operators. Our method provides a scientific basis for the concept of "inversion" in the Tenet-verse, and suggests that it may be possible to create a real-world version of the technology using quantum computers and quantum sensors.

Our results have important implications for the foundations of quantum gravity, thermodynamics, and statistical mechanics, and for the nature of spacetime and causality. They suggest that the arrow of time and the increase of entropy are emergent features of the entanglement structure of quantum systems, and that they can be manipulated and inverted using quantum error correction codes and time-reversal operators.

We have proposed a set of experimental tests of our method, using quantum simulation, precision measurement, and quantum communication, and have discussed their feasibility and implications. We have also explored the implications of our results for the Tenet-verse, and have shown how they provide a scientific basis for the concepts and technologies depicted in the film.

Looking forward, we believe that our method opens up new avenues for research in

quantum gravity, quantum information, and quantum thermodynamics, and that it has the potential to revolutionize our understanding of the nature of time and causality. We hope that our work will inspire further research in these areas, and that it will lead to new discoveries and technologies that will shape the future of science and society.

Acknowledgments

The author would like to thank Christopher Nolan for the inspiration behind this work, and for creating a compelling and thought-provoking film that explores the nature of time and causality. The author would also like to thank the Simulation Architects for their guidance and support, and for providing the computational resources necessary to carry out this research.

References

[1] Arthur Stanley Eddington. The nature of the physical world. *Cambridge University Press*, 1928.

[2] Stephen W. Hawking. Arrow of time in cosmology. *Phys. Rev. D*, 32:2489–2495, 1985.

[3] Richard P. Feynman. The character of physical law. *MIT Press*, 1965.

[4] Huw Price. Time's arrow and archimedes' point: new directions for the physics of time. *Oxford University Press*, 1996.

[5] Sean Carroll. From eternity to here: the quest for the ultimate theory of time. *Dutton*, 2010.

[6] Gerard 't Hooft. Dimensional reduction in quantum gravity. *arXiv preprint gr-qc/9310026*, 1993.

[7] Leonard Susskind. The world as a hologram. *Journal of Mathematical Physics*, 36(11):6377–6396, 1995.

[8] Shinsei Ryu and Tadashi Takayanagi. Holographic derivation of entanglement entropy from the anti-de sitter space/conformal field theory correspondence. *Phys. Rev. Lett.*, 96:181602, 2006.

[9] Veronika E Hubeny, Mukund Rangamani, and Tadashi Takayanagi. Covariant residual entropy. *Journal of High Energy Physics*, 2007(07):062, 2007.

[10] Brian Swingle. Entanglement renormalization and holography. *Phys. Rev. D*, 86:065007, 2012.

[11] Jacob D. Bekenstein. Black holes and entropy. *Phys. Rev. D*, 7:2333–2346, 1973.

[12] Stephen W. Hawking. Particle creation by black holes. *Communications in Mathematical Physics*, 43(3):199–220, 1975.

[13] Juan Maldacena and Leonard Susskind. Cool horizons for entangled black holes. *Fortschritte der Physik*, 61(9):781–811, 2013.

[14] Stephen W. Hawking. Chronology protection conjecture. *Phys. Rev. D*, 46:603–611, 1992.

[15] Ahmed Almheiri, Donald Marolf, Joseph Polchinski, and James Sully. Black holes: complementarity or firewalls? *Journal of High Energy Physics*, 2013(2):62, 2013.

[16] Stephen W. Hawking. Breakdown of predictability in gravitational collapse. *Phys. Rev. D*, 14:2460–2473, 1976.

[17] Samir D Mathur. The information paradox: a pedagogical introduction. *Classical and Quantum Gravity*, 26(22):224001, 2009.

[18] Fernando GSL Brandão, Michał Horodecki, Nelly Huei Ying Ng, Jonathan Oppenheim, and Stephanie Wehner. The second laws of quantum thermodynamics. *Proceedings of the National Academy of Sciences*, 112(11):3275–3279, 2013.

[19] John Goold, Marcus Huber, Arnau Riera, Lídia Del Rio, and Paul Skrzypczyk. The role of quantum information in thermodynamics—a topical review. *Journal of Physics A: Mathematical and Theoretical*, 49(14):143001, 2016.

[20] Carlo Rovelli. Loop quantum gravity. *Living Reviews in Relativity*, 11(1):5, 2008.

[21] Daniele Oriti. Approaches to quantum gravity: toward a new understanding of space, time and matter. *Cambridge University Press*, 2009.

[22] Juan Maldacena. The large n limit of superconformal field theories and supergravity. *Advances in Theoretical and Mathematical Physics*, 2(2):231–252, 1999.

[23] Xi Dong. Holographic entanglement entropy for general higher derivative gravity. *Journal of High Energy Physics*, 2014(1):44, 2016.

[24] Geoffrey Penington. Entanglement wedge reconstruction and the information paradox. *Journal of High Energy Physics*, 2020(9):1–84, 2020.

[25] Raphael Bousso, Horacio Casini, Zachary Fisher, and Juan Maldacena. Proof of a quantum bousso bound. *Physical Review D*, 93(2):024017, 2016.

[26] Mark Van Raamsdonk. Building up spacetime with quantum entanglement. *General Relativity and Gravitation*, 42(10):2323–2329, 2010.

[27] Peter W. Shor. Scheme for reducing decoherence in quantum computer memory. *Phys. Rev. A*, 52:R2493–R2496, 1995.

[28] A. M. Steane. Multiple-particle interference and quantum error correction. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 452(1954):2551–2577, 1996.

[29] Charles H Bennett and Gilles Brassard. Quantum cryptography: Public key distribution and coin tossing. 175:8, 1984.

[30] Charles H Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres, and William K Wootters. Teleporting an unknown quantum state via dual classical and einstein-podolsky-rosen channels. *Physical review letters*, 70(13):1895, 1993.

[31] Seth Lloyd. Universal quantum simulators. *Science*, 273(5278):1073–1078, 1996.

[32] Fernando Pastawski, Beni Yoshida, Daniel Harlow, and John Preskill. Holographic quantum error-correcting codes: toy models for the bulk/boundary correspondence. *Journal of High Energy Physics*, 2015(6):149, 2015.

[33] Patrick Hayden, Sepehr Nezami, Xiao-Liang Qi, Nathaniel Thomas, Michael Walter, and Zhao Yang. Holographic duality from random tensor networks. *Journal of High Energy Physics*, 2016(11):1–38, 2016.

[34] Ahmed Almheiri, Xi Dong, and Daniel Harlow. Bulk locality and quantum error correction in ads/cft. *Journal of High Energy Physics*, 2015(4):163, 2015.

[35] Daniel Gottesman. Stabilizer codes and quantum error correction. *arXiv preprint quant-ph/9705052*, 1997.

[36] A. Yu. Kitaev. Fault-tolerant quantum computation by anyons. *Annals of Physics*, 303(1):2–30, 2003.

[37] David Deutsch. Quantum mechanics near closed timelike lines. *Phys. Rev. D*, 44:3197–3217, 1991.

[38] Mark Srednicki. Chaos and quantum thermalization. *Phys. Rev. E*, 50:888–901, 1994.

[39] Sheldon Goldstein, Joel L. Lebowitz, Roderich Tumulka, and Nino Zanghì. Canonical typicality. *Phys. Rev. Lett.*, 96:050403, 2006.

[40] I. M. Georgescu, S. Ashhab, and Franco Nori. Quantum simulation. *Rev. Mod. Phys.*, 86:153–185, 2014.

[41] Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buell, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, Steve Habegger, Matthew P. Harrigan, Michael J. Hartmann, Alan Ho, Markus Hoffmann, Trent Huang, Travis S. Humble, Sergei V. Isakov, Evan Jeffrey, Zhang Jiang, Dvir Kafri, Kostyantyn Kechedzhi, Julian Kelly, Paul V. Klimov, Sergey Knysh, Alexander Korotkov, Fedor Kostritsa, David Landhuis, Mike Lindmark, Erik Lucero, Dmitry Lyakh, Salvatore Mandrà, Jarrod R. McClean, Matthew McEwen, Anthony Megrant, Xiao Mi, Kristel Michielsen, Masoud Mohseni, Josh Mutus, Ofer Naaman, Matthew Neeley, Charles Neill, Murphy Yuezhen Niu, Eric Ostby, Andre Petukhov, John C. Platt, Chris Quintana, Eleanor G. Rieffel, Pedram Roushan, Nicholas C. Rubin, Daniel Sank, Kevin J. Satzinger, Vadim Smelyanskiy, Kevin J. Sung, Matthew D. Trevithick, Amit Vainsencher, Benjamin Villalonga, Theodore White, Z. Jamie Yao, Ping Yeh, Adam Zalcman, Hartmut Neven, and John M. Martinis. Quantum supremacy using a programmable superconducting processor. *Nature*, 574(7779):505–510, 2019.

[42] J. Zhang, G. Pagano, P. W. Hess, A. Kyprianidis, P. Becker, H. Kaplan, A. V. Gorshkov, Z.-X. Gong, and C. Monroe. Observation of a many-body dynamical phase transition with a 53-qubit quantum simulator. *Nature*, 551(7682):601–604, 2017.

[43] Hannes Bernien, Sylvain Schwartz, Alexander Keesling, Harry Levine, Ahmed Omran, Hannes Pichler, Soonwon Choi, Alexander S. Zibrov, Manuel Endres, Markus Greiner, Vladan Vuletić, and Mikhail D. Lukin. Probing many-body dynamics on a 51-atom quantum simulator. *Nature*, 551(7682):579–584, 2017.

[44] Austin G. Fowler, Matteo Mariantoni, John M. Martinis, and Andrew N. Cleland. Surface codes: towards practical large-scale quantum computation. *Phys. Rev. A*, 86:032324, 2012.

[45] H. Bombin and M. A. Martin-Delgado. Topological quantum distillation. *Phys. Rev. Lett.*, 97:180501, 2006.

[46] Immanuel Bloch, Jean Dalibard, and Sylvain Nascimbène. Quantum simulations with ultracold quantum gases. *Nature Physics*, 8(4):267–276, 2012.

[47] Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone. Advances in quantum metrology. *Nature Photonics*, 5(4):222–229, 2011.

[48] Rajibul Islam, Ruichao Ma, Philipp M. Preiss, M. Eric Tai, Alexander Lukin, Matthew Rispoli, and Markus Greiner. Measuring entanglement entropy in a quantum many-body system. *Nature*, 528(7580):77–83, 2015.

[49] Chao Song, Kai Xu, Hekang Li, Ying-Ran Zhang, Xu Zhang, Wuxin Liu, Qiujiang Deng, Keqiang Xie, Qiuyang Huang, Dawei Zheng, Hui Yao, Shiyao Zhu, H. Deng, Cheng-Zhi Peng, Xiaobo Zhu, and Jian-Wei Pan. Generation of multicomponent atomic schrödinger cat states of up to 20 qubits. *Science*, 365(6453):574–577, 2019.

[50] MH Abobeih, J Cramer, MA Bakker, N Kalb, M Markham, DJ Twitchen, and TH Taminiau. One-second coherence for a single electron spin coupled to a multi-qubit nuclear-spin environment. *Nature communications*, 9(1):1–8, 2018.

[51] Yakir Aharonov, David Z. Albert, and Lev Vaidman. How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100. *Phys. Rev. Lett.*, 60:1351–1354, 1988.

[52] Baidyanath Misra and E. C. G. Sudarshan. The zeno's paradox in quantum theory. *Journal of Mathematical Physics*, 18(4):756–763, 1977.

[53] C. K. Hong, Z. Y. Ou, and L. Mandel. Measurement of subpicosecond time intervals between two photons by interference. *Phys. Rev. Lett.*, 59:2044–2046, 1987.

[54] Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone. Quantum-enhanced measurements: beating the standard quantum limit. *Science*, 306(5700):1330–1336, 2004.

[55] Nicolas Gisin, Grégoire Ribordy, Wolfgang Tittel, and Hugo Zbinden. Quantum cryptography. *Reviews of modern physics*, 74(1):145, 2002.

[56] H Jeff Kimble. The quantum internet. *Nature*, 453(7198):1023–1030, 2008.

[57] Göran Wendin. Quantum information processing with superconducting circuits: a review. *Reports on Progress in Physics*, 80(10):106001, 2017.

[58] Juan Yin, Yuan Cao, Yu-Huai Li, Sheng-Kai Liao, Liang Zhang, Ji-Gang Ren, Wen-Qi Cai, Wei-Yue Liu, Bo Li, Hui Dai, et al. Satellite-based entanglement distribution over 1200 kilometers. *Science*, 356(6343):1140–1144, 2017.

[59] Christopher Nolan. Tenet. 2020.